OCCUPATIONAL HEALTH
AND
SAFETY GUIDE
INTERIM

GLASS AND PLASTIC WINDOW DESIGN FOR PRESSURE VESSELS	1.4.2

I. INTRODUCTION

The ASME Code outlines criteria and lists the maximum allowable stress values for most pressure vessel materials. At this time, however, it does not cover glass or plastic materials. Since these materials are frequently used as windows in pressure vessels at BNL, this Guide provides a method to achieve uniformity, reliability and safety when designing with these materials.

II. SCOPE

The rules in this Guide establish BNL minimum acceptable requirements for the design and installation of untempered* glass and plastic windows in pressure vessels above the cryogenic temperature range.

Occupational Health and Safety Guide No. 1.4.1 (Pressure Systems) applies to all other aspects of the pressure vessel.

This Guide lists mechanical properties of various glass and plastic materials and specifies the allowable design stresses.

Additionally, suggested mounting designs, assembly procedures and testing requirements are included.

A non-mandatory appendix is included which provides information to aid in the design of windows.

III. RESPONSIBILITIES

A. ***The Department Chairman/Division Head*** of the user/designers is responsible for:

1. Assuring that any pressure vessel utilizing glass or plastic windows that is designed by or for his department is in compliance with the requirements of this Guide.
2. Ensuring that adequate documentation in the form of engineering drawings, specifications, and stress calculations are available to all interested parties.

B. ***The Department Chairman/Division Head*** of the facility is responsible for:

1. Assuring that any pressure vessel utilizing glass or plastic windows that is operated within his facilities is in compliance with the requirements of this Guide.
2. Assuring that an independent review has been performed by an individual or committee appointed by the Department Chairman or Chairman of Laboratory Safety Committee.

C. ***The Safety and Environmental Protection Division*** is responsible for:

1. Assisting the design or review groups in the interpretation of the requirements of this Guide.
2. Auditing departments for compliance with this Guide.

This Guide does not discount the use of tempered glass, providing certification as to the ultimate stress is supplied from the manufacturer, and a safety factor of 10 is applied to the ultimate to arrive at the allowable design stress.

IV. MATERIALS

A. *Glass and Methyl Methacrylate*

Glass is much stronger under compressive loads than under tensile loads. When loaded to the point of failure, glass exhibits no yield point and fails from a tensile stress or tensile component. Due to its nonductility, a small imperfection in the surface of glass will cause a stress concentration under load which may be many times greater than the nominal stress at the same point. There is not equalization or relief of these stresses and fracture may result from the propagation of this flaw.

Strength of glass windows depends on the thickness to unsupported width ratio, but it is essential to realize that failure is also determined by the design of the mounting, the characteristics of the gasket material and the assembly procedures. These matters must be given proper consideration in order to provide adequate safety factors.

Two commonly used materials are “fused silica” (quartz) and “methyl methacrylate” (Lucite or Plexiglas). These two transparent materials are selected mainly for their optical properties (high transmittance of ultraviolet light). Stipulation of recommended design stresses for these two materials is complicated by factors of surface condition, duration of load, rate of change of load, temperature, etc.

The following rules were used to provide a basis for determining the allowable design stresses contained in Table I, Mechanical Properties of Glass & Methyl Methacrylate.

1. The long-term stress (infinite duration) will be used as the limit.
2. Although optical materials can be initially fabricated with highly polished surfaces, it is impossible to guarantee against the incurrence of occasional surface defects that reduce the load carrying ability of the finished window. As a result, all stress limits will be based on manufacturer’s published values for the tensile strength of fused silica (and glass in general) in the abraded condition.
3. Failure of a window cannot be limited to that of a catastrophic shattering. A methyl methacrylate window that deforms excessively under combined pressure-temperature effects has also functionally failed since it would permit leakage past its seals (see Reference 8b). In this last case the design limit is not necessarily stress, since a lowering of the elastic modulus due to thermal effects would cause a failure of excessive deflection. The allowable stress for methyl methacrylate will be reduced as the operating temperature rises above 70°F. See Reference 8 for method used to calculate reduced design limits.
4. Due to the lack of repeatability in the load carrying ability of brittle materials, a safety factor of 10 of the tensile strength of the given material was used to determine the allowable tensile stress.

B *Plastics*

The general category of plastics covers a broad range of materials. The ease of forming these materials, either by heat or pressure, coupled with high tensile strength and excellent resistance to chemicals, makes plastics a highly popular material at BNL for use as windows in pressure or vacuum applications.

A typically desirable plastic film is Mylar. Mylar is made from polyethylene terephthalate, the polymer formed by the condensation reaction of ethylene glycol and terephthalic acid. Its unusual balance of properties enables it to serve specific engineering functions at the Laboratory. It has excellent resistance to a broad range of chemicals at room temperature including aliphatic hydrocarbons, gasoline, carbon tetrachloride, perchloreythylene, oils, fats, alcohols, glycols, esters, ethers and dilute acids and bases. It is attacked by strong acids and bases.

Mylar is available in several types, although for the purposes of this standard, Type A will be assumed, unless material certification is available. The allowable design stresses shall be as noted in Table II, Typical Properties of Plastics. Materials other than those listed in the table may be acceptable, provided test results and documentation are available.

In addition to the mechanical properties, there are certain common materials which may be susceptible to degradation resulting from radiation damage. These effects should be taken into account when designing windows to be used in radiation fields. See Figures 6 thru 13 for effect of radiation on mechanical properties of certain materials.

The experimenter is responsible for supplying appropriate data to ensure that the window material and filling agent are compatible.

1. The following tests and conditions shall apply for all windows whose calculated deflection is greater than ten times the actual window thickness.

   a. A window shall be cycled a minimum of 3 times at 50% over operating pressure to demonstrate its integrity in going from load to no load conditions, with its maximum deflection being monitored at each cycle and the magnitude of the maximum deflection at the end of the third cycle taken as a base line. These tests should be witnessed by both a representative of the Safety and Environmental Protection and the facility. Any subsequent deformation during operation that exceeds the maximum deflection established at the third cycle by 10% shall be deemed grounds for changing the window.

   b. For a vessel such as a Cerenkov counter, which may be evacuated and then pressurized, the monitoring of the maximum deflection shall be done under the positive pressure side of the cycle but the window shall still be cycled a minimum of 3 times to demonstrate its integrity.

   c. All windows will be subjected to a visual inspection for scratches, pockmarks or wrinkles prior to evacuation or pressurizing. This inspection to be witnessed by a representative of the Safety and Environmental Protection Division immediately prior to pressure testing.

   d. The experimenter is responsible for supplying appropriate data to ensure that the window material and the vessel contents are compatible.

   e. If multilayers are to be considered (since this is a specialized area in which the behavior is not as predictable as in single layer windows) each design shall be subject to a particularly stringent review.

2. All other plastic windows shall be tested in accordance with Occupational Health and Safety Guide No. 1.4.1, "Pressure Systems."

V. DESIGN GUIDELINES

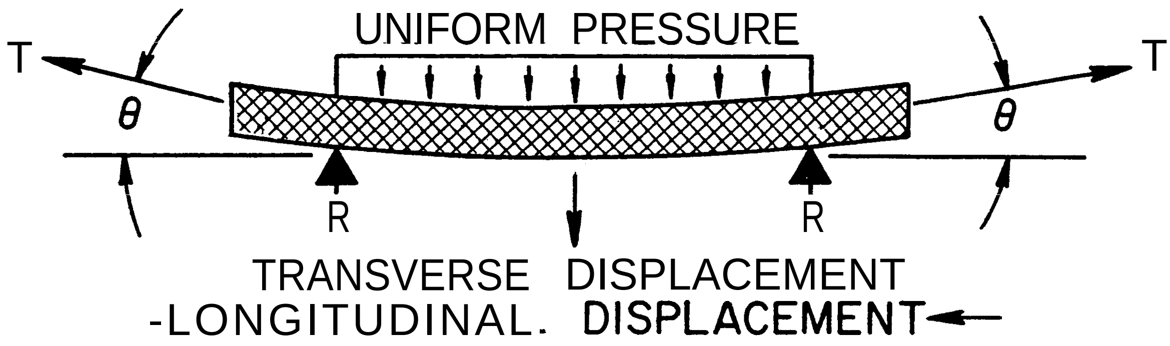
A. The behavior of a flat window under the influence of a uniform pressure varies from that of a "Flat Plate," where only bending stress is relevant, to that of a "Membrane" or "Diaphragm," where only membrane stress is relevant.

Only three types of window mountings are permitted. Definitions of the three are given in SEC. VA1, VA2, and VA3 while specific design guidelines are given in SEC. VB, VC and VD.

1. Free Edges (Simply Supported): A condition of support at the edge of a window that prevents transverse displacement of the edge, but permits rotation and longitudinal displacement. (T = 0, θ not equal to zero, see diagram below.) See Figures 14 and 15.

2. Held-But-Not-Fixed: A condition of support at the edge of a window that prevents transverse displacement and longitudinal displacement of the edge, but permits rotation. (T not equal to zero, θ not equal to zero, see diagram below.) See Figure 16.

3. Held and Fixed: A condition of support at the edge of a window that prevents transverse displacement, longitudinal displacement and rotation of the edge. (T not equal to zero, $\theta = 0$, see diagram below.) See Figure 17.



R .... Reaction force of Window Support (prevents transverse displacement)
θ .... Angle of Window Edge at Support (Due to rotation)
T .... Window Edge Tension (Force sufficient to prevent any longitudinal motion of window edge towards the center)

4. Limiting: Conditions:

a. All window mount designs will be classed "Held-But-Not-Fixed"unless the conditions of "Held and Fixed" are met per the definition of SEC. VA3 and the design guidelines of SEC. VD.

b. All window mount designs qualifying as "Held and Fixed" must have the stress checked at the edge as well as at the center.

B. ***Glass and "Free Edge" Mount***

Although the compressive strength of glass is rather high, the brittle nature of the material necessitates caution in design in order to eliminate unpredictable failures at relatively low values of tensile stress. This can occur because of the inability of the material to relieve high local stresses around flaws or other areas where high stress concentration effects exist. Thus, the following guidelines should be observed.

1. General rules are as follows:

a. The shape of the glass should be simple.

b. Sharp corners or sudden changes in cross section should be avoided.

c. Tensile stress areas should be free from flaws.

d. The edge should be beveled and non-optical surfaces should be polished or etched.

e. If fiducial marks are required to be inscribed in the glass, they should only be on surfaces which are under compression during any operating or test condition.

f. The glass should have no bolting holes or relieved sections for bolts.

g. Calculated stress based on actual measured thickness must be equal to or less than the design stress in Table I (or Table II for plastics).

2. The mounting for the window should be designed so that concentrated clamping loads do not produce any edge bending moments or any restraint on longitudinal deformations. General rules are as follows:

a. Load transmitting materials in contact with the window should be significantly softer than the window material and should be limited to elastomeric compositions, paper or asbestos packing materials or relatively soft materials such as Teflon or Indium. (See Figures 14 and 15 for suggested mounting.)

b. The clamping force on the window should be controlled in order to prevent accidental overload. It is recommended that the bolting for this purpose be designed to limit the compressive unit force on the glass to about 1500 psi by proper selection of the size and number of bolts. (See Reference 11)

c. The design of the mount for the window should take into account:

i. the effect of deformation of the mount due to the clamping loads

ii. possible deflections due to the loading condition on the vessel.

d. The mount should be designed so that provisions for relative motion, such as those caused by thermal or pressure changes, between the glass and mount are sufficient to prevent loading conditions that would exceed the allowable stress. It is therefore recommended that adhesive bonded joints between the glass and metal parts be avoided.

C. Plastics and "Held-But-Not-Fixed" Mount

The general guidelines listed for glass should also be followed for plastics. In addition the following guides should be observed for plastics, with particular care required when using materials that behave as membranes.

1. The following distance relationships should be observed (see Figures 16 and 17).

a. The distance from bolt hole to O-ring groove should be at least 2/3 of the bolt diameter. (Dimension B)

b. The distance from the O-ring groove to the window opening should be at least 1/8" plus the radius. (Dimension A)

c. The window opening edge radius should be a minimum of 15 times the window thickness although 25 is preferred.

d. For rectangular window mounts, the corner radius shall be a minimum of .15 of the shortest span of the window opening (see Fig. 18).

2. Suggested O-ring groove dimensions are included in Table III. All surface finishes shall be 64 micro-inches or better, free of burrs and sharp edges. Clamping surfaces must be flat to within 0.0015"/ft.

3.' The clamping bolt size shall be large enough so that the applied bolt torque will exert a clamping force that will be a factor of 3 greater than the load applied to the window. (See Reference #12)

4. The clamping ring must be rigid enough to maintain adequate clamping force between bolts.

5. Flat washers shall be used under the bolt heads to prevent galling and to ensure the application of the proper torque value.

6. All bolt holes made in film windows shall be punched with a sharp edged punch. The diameter is to be the same as the recommended clearance hole for bolts. Do not burn the bolt holes. Deburr all holes after punching has been completed.

7. For suggested means of clamping, see Fig. 16 or Fig. 17.

8. Tensile stress in the window material shall be based on actual measured thicknesses and should not exceed the allowable design stress as specified in Table II.

D. *Plastics and 'Held and Fixed" Mount*

The general guidelines listed for the "Held-and-Fixed" mount apply in addition to the following conditions:

1. The clamping ring and vessel wall must be rigid enough to prevent any local deflections that would permit angular rotation of the window edges.

2. The window must have significant flexural stiffness.

3. Since practical compliance with the requirements for a "Held and Fixed" mount is very difficult, any design considering this alternative must be subjected to review per SEC. III.

TABLE I
MECHANICAL PROPERTIES OF GLASS & METHYL METHACRYLATE

Material	Temperature Range (“F)	Elastic Modulus (psi) "E"	Modulus of Rigidity (psi) "C"	Poisson’s Ratio "υ"	Tensile Strength (psi)	Reference	Allowable Design Stress (psi)
Fused Silica (Quartz)	0 - 300	$10.5x10^6$	$4.5x10^6$	0.16	6,800	Note #1	680
Methyl Methacrylate	0	500.000			12,200	See Fig. 4,	I.220
(Plexiglass, Lucite)	25	460.000			1 I.300		1.130
	50	410,000			10,400		I.040
	75	360,000	130,000	0.39	9,200	Note #2	920
	100	300,000			7,900	&	770
	125	250,000			6,500	Note #8	640
	150	180,000			4,700		460
Aluminosilicate Glass-Corning Code 1723	0 - 300	$12.4x10^6$	$4.9x10^6$	0.26	6,630	Note #3	660
96% Silica Glass Corning Code 7900 (Vycor)	0 - 300	$10x10^6$ psi	$4.2x10^6$	0.19	6,150	Note #3	615
Borosilicate Glass Corning Code 7740 (Pyrex)	0 - 300	$9.1x10^6$	$3.8x10^6$	0.20	6,100	Note #3	610
Polished Plate Glass Pittsburgh Plate Glass - “Herculite”	0 - 300	$10x10^6$	$4.1x10^6$	0.21	6,500 (annealed) * 29,500 (tempered)	Note #4	650 (annealed) * 2,950 (tempered)
High Lead Glass (61% Lead Oxide) X-Ray Glass	0 - 300	$8x10^6$	$3.3x10^6$	0.23	5,000	Note #4	500
Borosilicate Crown Optical Glass (Schott BK-7)	0 - 300	$11.6x10^6$	$4.8x10^6$	0.20	5,000	Note #5	500

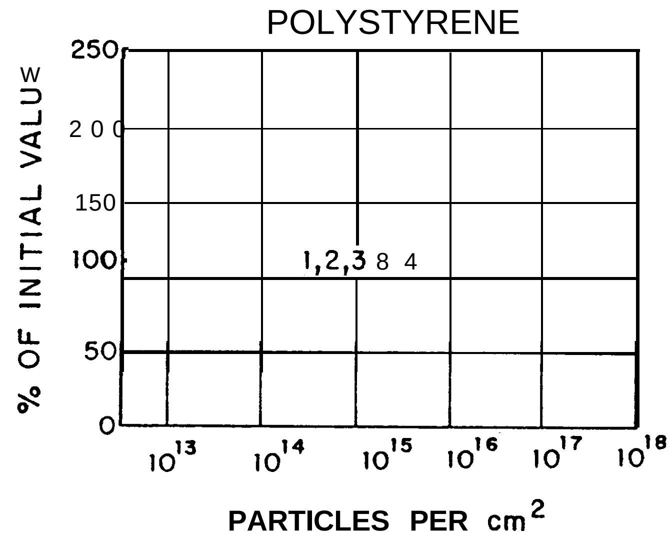
* Maximum attainable value for full temper

TABLE II
TYPICAL PROPERTIES OF PLASTICS

Material	Temp °F	Yield Strength PSI	Tensile Strength PSI	Elastic Modulus PSI	Refractive Index	Thermal Expansion 10^5/°F	Radiation Stability	Allowable Design Stress PSI
Mylar-Type A	-100	28000	32000	7×10^5				
	70	12500	25000	5×10^5	1.64	1.5	Fig. 2	9500
	200	8000	19000	1.1×10^5				
	300	5500	12000	0.6×10^5				
Polycarbonate	- 40		13000	4.0×10^5				2000
(Lexan)	70	8000	9500	3.25×10^5	1.586	3.75	Fig. 6	2000
	212		5500	2.20×10^5				500
Nylon	- 40		15700	4.7×10^5				2500
(Zytel 101)	73	11800	11800	4.1×10^5	1.53	5.5		2000
	170		9000	1.0×10^5	(translucent)			1500
Polyimide (Kapton)	-300	NONE	35000	5.1×10^5				
	77	10000	25000	4.3×10^5	1.78	2.0		
	392	6000	17000	2.6×10^5	(translucent)			
Polystyrene (Hi-impact)	77	3500	6500	4×10^5	1.57	3.4	Fig. 1	
Acetal (Delrin)	- 68	14700	14700					3675
	73	10000	10000	4.1×10^5	1.48	4.5	Fig. 3	2500
	158	7500	7500	2.2×10^5				1875
Kel-F (Grade II)	77	4920	5650	1.5×10^5				1400
	158	1400	3020	$.58\times10^5$		4.8		750
	258	290	525	$.05\times10^5$				100
Aclar (22A)*	70	8000 (1 mil)	13300	1.4×10^5				
		5000 (5 mil)						
Polyvinyl Chloride	75		7200					
(PVC)	140		4900	4×10^5	1.5	3.0		
	180		3200					

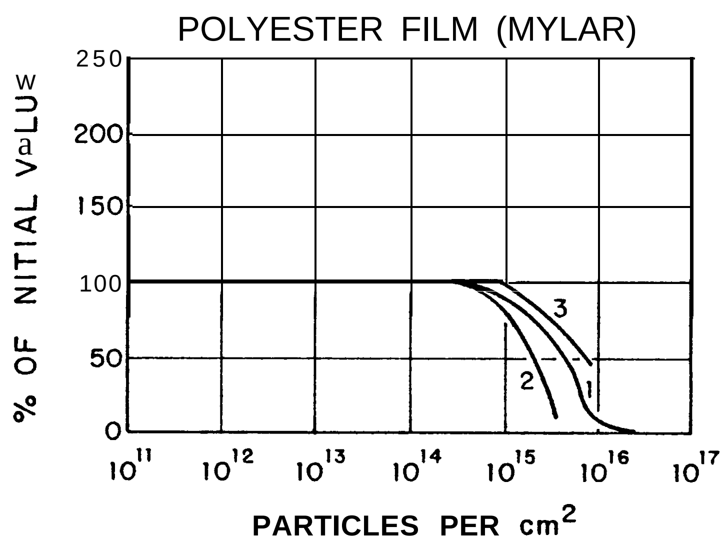
* Remains pliable at cryogenic temperatures

EFFECT OF RADIATION ON MECHANICAL PROPERTIES



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION
3	ELASTIC MOOULUS
4	SHEAR STRENGTH

FIG. 6

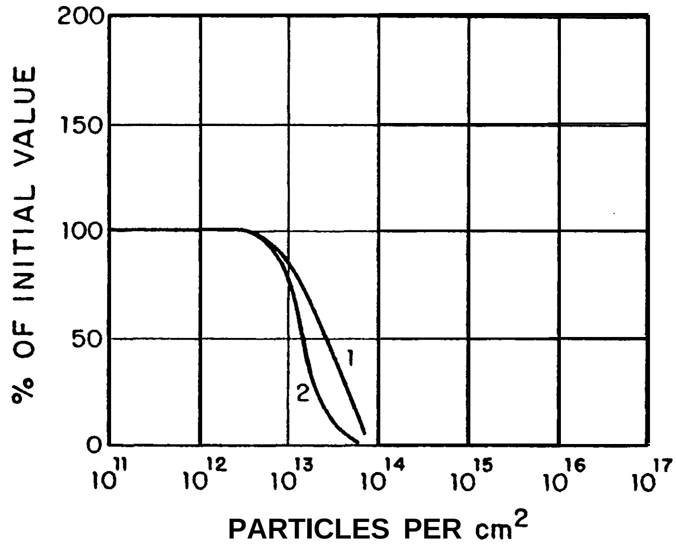


CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION
3	ELASTIC MOOULUS

FIG. 7

EFFECT OF RADIATION ON MECHANICAL PROPERTIES

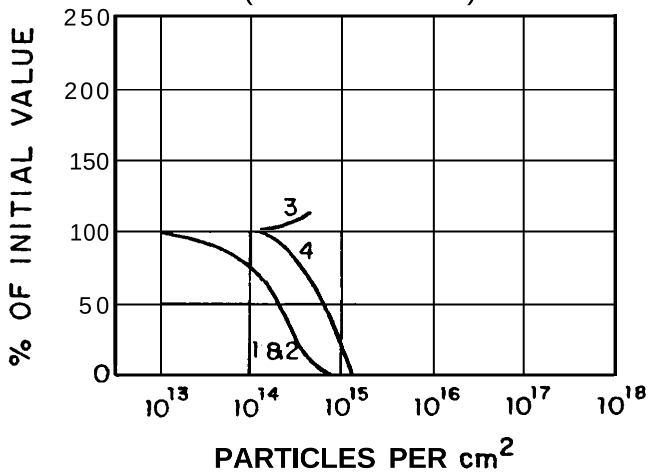
ACETAL RESIN (DELRIN)



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION

FIG. 8

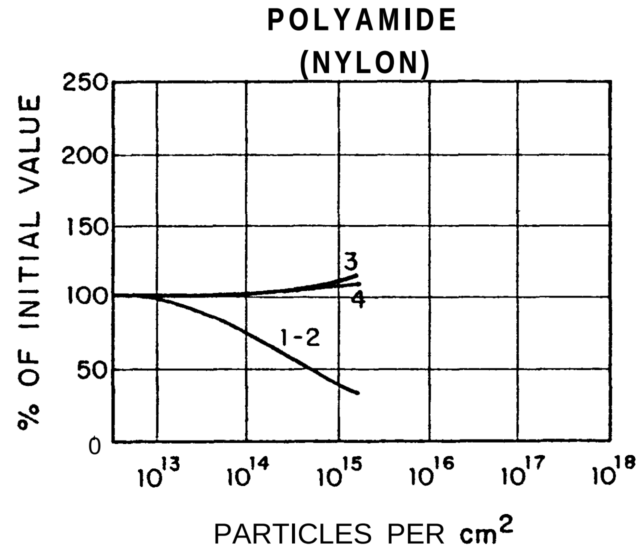
ACRYLIC RESIN: POLYMETHYLMETHACRYLATE (PLEXIGLASS)



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION
3	ELASTIC MODULUS
4	SHEAR STRENGTH

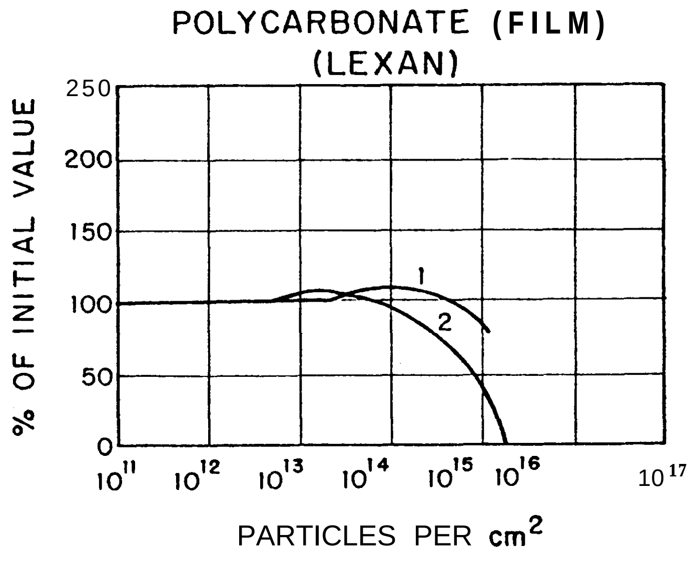
FIG. 9

EFFECT OF RADIATION ON MECHANICAL PROPERTIES



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION
3	ELASTIC MODULUS
4	SHEAR STRENGTH

FIG. 10

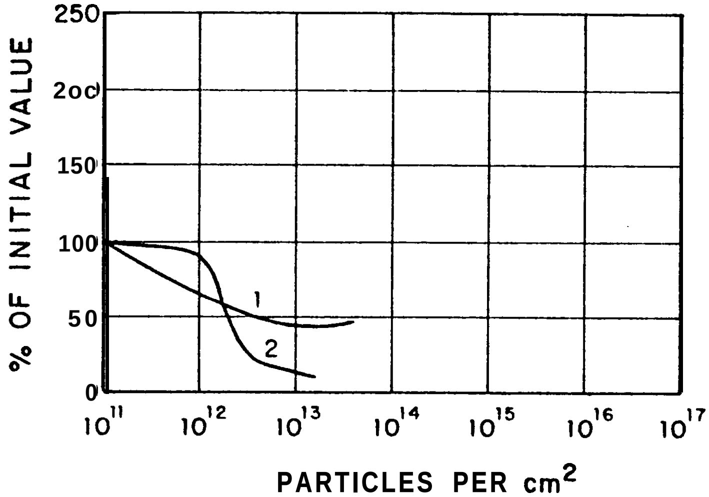


CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION

FIG. 11

EFFECT OF RADIATION ON MECHANICAL PROPERTIES

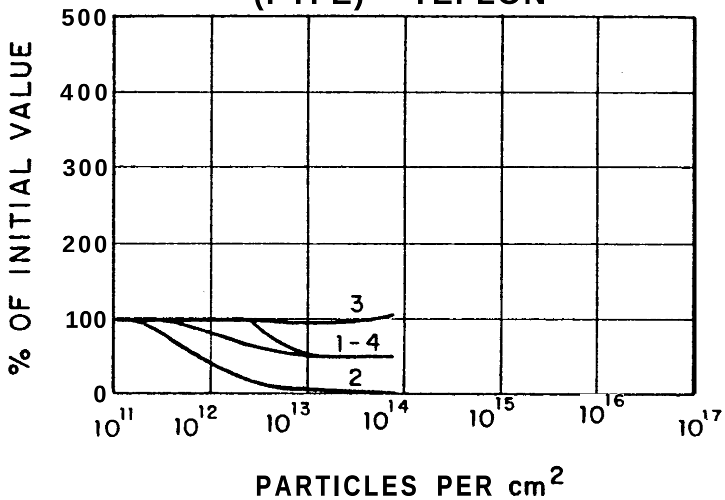
TEFLON FEP



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION

FIG. 12

POLYTETRAFLUOROETHYLENE (PTFE) "TEFLON"



CURVE	PROPERTY
1	TENSILE STRENGTH
2	ELONGATION
3	ELASTIC MODULUS
4	SHEAR STRENGTH

FIG. 13

Table III

"O" RING GROOVE WIDTHS AND DEPTHS

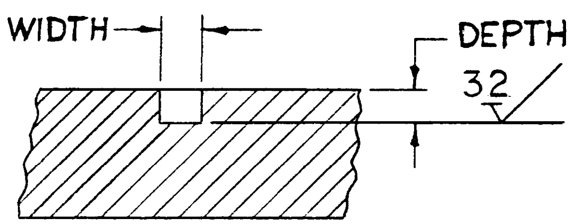
	Face Seals			Peripheral Seals	
Nom. Dia.	cross Section Dia. (D)	Groove Depth (.75D)	Groove Width (1.2D) +.005 -.000	Groove Depth (.8D)	Groove Width (1.15D)+.005 -.000
1/16	.070±.003	.050/.053	,084	.054/.056	.081
3/32	.103±.003	.077/.080	.124	.080/.082	.118
1/8	.139±.004	.104/.107	.167	.108/.117	.160
3/16	.210±.005	.156/.160	,281	.165/. 168	.242
1/4	.275±.006	.206/.210	.343	.217/.220	.316

The same groove dimensions (above, except for peripheral seals) are used for both the rubber O-rings and the metal C-rings.

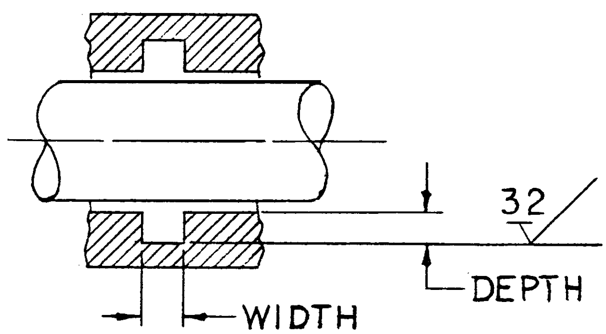
NOTE 1 - Groove widths are minimum figures. When designing grooves in flanges, the inner diameter of the "O" ring groove should be made slightly larger than the actual inner diameter of the "O" ring. In general, this works out to be the nominal inside diameter of the "O" ring.

NOTE 2 - For rotating and peripheral seals 1-1/2 O.D. and larger use .85D for groove depth, (rubber seals only).

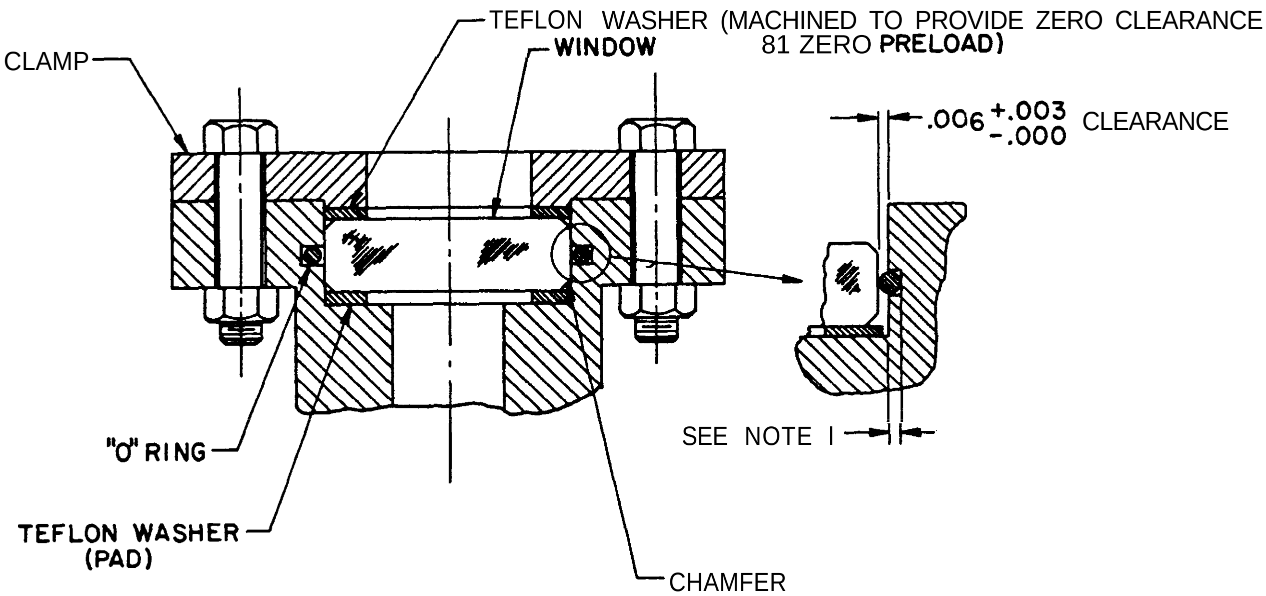
Static Seal



Peripheral Seal
Rubber Seal Onlv



WINDOW MOUNT
(FREE EDGES)



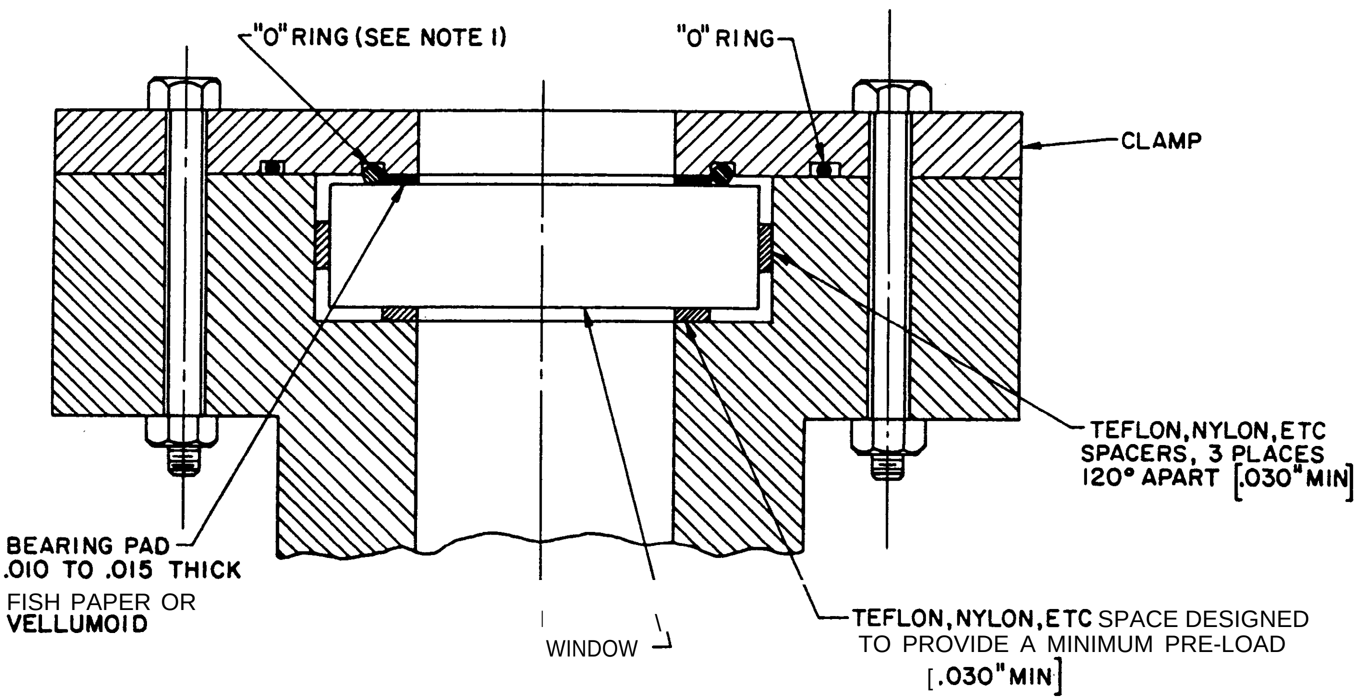
NOTES :

I-GROOVE DEPTH TO BE .006" LESS THAN INDICATED IN TABLE III,. PAGE 18.

Z-WINDOW MOUNT IS CLASSED "FREE EDGES" BECAUSE THE TEFLON PADS CANNOT PROVIDE ANY EDGE TENSION, AND ONLY MINIMAL RESTRAINT OF ANGULAR ROTATION OF WINDOW EDGES.

FIG 14

WINDOW MOUNT
(FREE EDGES)



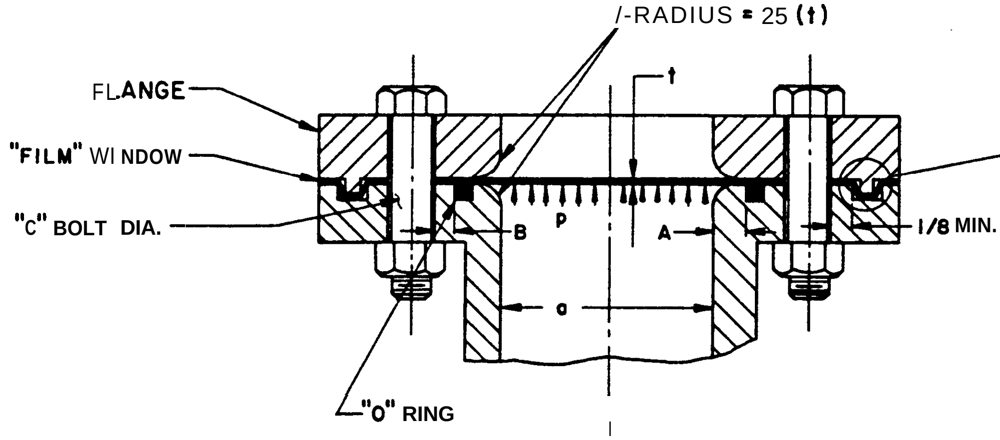
NOTES :

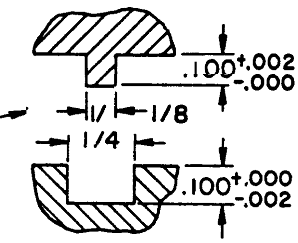
1- THE "O" RING MUST BE 1/8" DIAMETER OR LARGER. THE "O" RING GROOVE DEPTH IS TO BE DEPTH SPECIFIED IN TABLE III, PAGE 18 MINUS THE THICKNESS OF THE BEARING PAD.

2-WINDOW MOUNT IS CLASSED "FREE EDGES" **BECAUSE THERE CANNOT BE ANY EDGE** TENSION OR RESTRAINT **OF ANGULAR ROTATION OF WINDOW EDGES.**

FIG 15

WINDOW MOUNT
HELD BUT NOT FIXED





CLAMP RING

NOTES:

I-CLAMP RING (OPTIONAL) PROVIDES ADDED HOLDING FOR THIN WINDOWS (MAX. THKNESS .042")

2-SEE TABLE III , PAGE 18, FOR "O" RING GROOVE DIM.

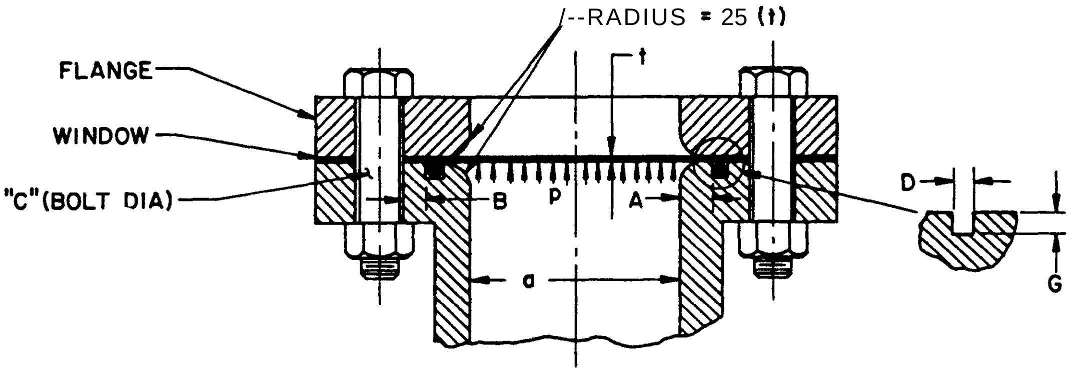
3-WINDOW MOUNT IS CLASSED "HELD BUT NOT FIXED" ONLY IF $p/E(a/t)^4 \geq 500$

4-THIS MOUNT CANNOT BE USED FOR WINDOWS MADE OF BRITTLE MATERIAL SUCH AS GLASS, QUARTZ OR METHYL METHACRYLATE

A = RADIUS + 1/8" MIN.
B = 2/3 C DIM. MIN.
t = WINDOW THICKNESS (IN.)
p = UNIFORM PRESSURE (PSI)
a = MINIMUM SPAN (IN.)
E = ELASTIC MODULUS (PSI) (WINDOW MATERIAL)

FIG 16

WINDOW MOUNT
(HELD AND FIXED)



A = RADIUS + 1/8" MIN.
B = 2/3 "C" DIM. MIN.
D&G SEE TABLE III, PAGE 18

t = WINDOW THICKNESS (IN.)
p = UNIFORM PRESSURE (PSI)
a = MINIMUM SPAN (IN.)
E = ELASTIC MODULUS (PSI) (WINDOW MATERIAL)

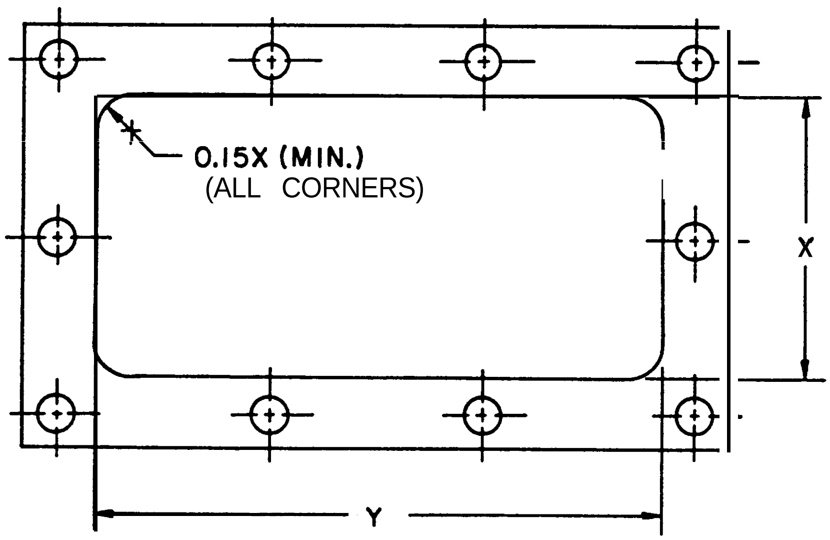
NOTES:

1-WINDOW MOUNT IS CLASSED "HELD AND FIXED" ONLY IF $p/E(a/t)^4 < 500$ AND THE STRESS AT THE EDGES IS BELOW THE YIELD POINT OF THE WINDOW MATERIAL.

2-WINDOW MOUNT IS CLASSED "HELD BUT NOT FIXED" IF EITHER OR BOTH CONDITIONS IN NOTE 1 ARE EXCEEDED

FIG. 17

FLANGE FOR RECTANGULAR FILM WINDOWS



NOTES:
1-WHERE "X" IS SMALLER OR EQUAL TO "Y"
2-ALL OTHER DEMENSIONS, REFER TO FIG. 16 & 17

FIG. 18

APPENDIX A

THICK PLATE THEORY

I. Symbol Definition

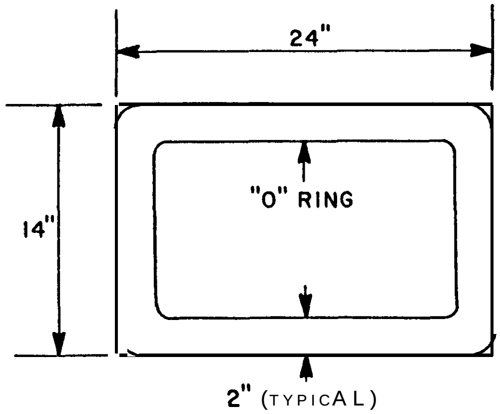
Symbol		Description	Unit
a		Shortest span	Inch
b		Longest span	Inch
t		Thickness	Inch
p		Uniform pressure load	PSI
w		Deflection (maximum at center)	Inch
θ		Edge Slope (positive - up to the right)	Radians
S_{des}		Design Stress (Table I or II)	PSI
E		Elastic Modulus (Table I or II)	PSI
S_a		Calculated Stress - "a" direction	PSI
S_B		Calculated Stress - "b" direction	PSI
γ		Poisson's Ratio	
K_1	Elliptic Windows	Coefficient for Stress - "a" direction	
K_2		Coefficient for Stress - "b" direction	
K_3		Coefficient for Deflection	
K_4		Coefficient for Edge Slope - "a" direction	
K_5	Rectangular Windows	Coefficient for Stress - "a" direction	
K_6		Coefficient for Stress - "b" direction	
K_7		Coefficient for Deflection	
K_8		Coefficient for Slope - "a" direction	

II. Thick Flat Plate Theory

A. Limiting Conditions

1. Maximum calculated deflection must be less than one-half the Plate thickness. (Brittle materials or glass)
2. Load is uniformly distributed over the entire surface.
3. All edges are simply supported.
4. The lower limiting case for elliptical windows is circular (b/a) = 1.
5. The lower limiting case for rectangular windows is square (b/a) = 1.
6. The upper limiting case for elliptical windows is identical to the upper limiting case for rectangular windows. (b/a) $\rightarrow \infty$
7. All coefficients and equations are based on material from "Theory of Plates and Shells" - Timoshenko - 2nd edition.

SAMPLE PROBLEMS



Operating Temperatures
20°C (68°F)
a = 14 - 2(2) = 10"
b = 24 - 2(2) = 20"
b/a = 2

Problem Number	Material	Pressure (PSI)	E (PSI)	Γ	S_{DES} (PSI)
1	Plate Glass	15	10×10^{6}	0.21	650
2	Polycarbonate	15	3.25×10^{5}	0.3	2000
3	Polycarbonate	3	3.25×10^{5}	0.3	2000
4	Polycarbonate	5	3.25×10^{5}	0.3	2000

Values of Elastic Modulus (E), Poisson's Ratio (γ), and Allowable Design Stress (Sdes) are found in Tables I and II. The Poisson's Ratio (γ) for polycarbonate is assumed equal to the average for most plastics, (approximately **0.3**). This assumption produces a negligible error in calculated values of stress and deflection.

If γ = **0.36** Calculated Stress = 2% low

Calculated Deflection = 7% high

Problem #1

Window edges must be "free."

Using b/a and Γ in Table A-l,

$$s_{des} = S_a = K_5 P\left(\frac{a}{t}\right)^2$$

$$S_b = K_6 P\left(\frac{a}{t}\right)^2$$

K_5 = 0.602-J
K_6 = 0.232
K_7 = 0.116
K_8 = 0.363

From Table A-2

$$w = K_7 \frac{pa^4}{Et^3}$$

$$\theta_{max} = K_8 \frac{pa^3}{Et^3}$$

Solve for theoretical window thickness:

$$S_{deo} = 650 = 0.602\ (15)\left(\frac{10}{t}\right)^2$$

$t = 1.179”$ use 1 3/16" (1.188”)

Check deflection for the limit:

$$w = \leq \frac{t}{2}$$

$$w = \frac{0.116\ (15)(10)^4}{10x10^6(1.188)^3} = 0.00104" \langle \frac{t}{2} = 0.590$$

$$S_a = 0.602(15)\left(\frac{10}{1.188}\right)^2 = 640 \text{ PSI}$$

$$S_b = 0.232(15)\left(\frac{10}{1.188}\right)^2 = 247 \text{ PSI}$$

$$\theta_{max} = \frac{0.363(15)(10)^3}{10x10^6(1.188)^3} = 0.00032 \text{ RAD } (0.0190”)$$

NOTE: The window support design must permit the outer 2” portion to rotate through the angle θmax without applying any significant restraining force.

Problem #2

All equations are the same as Problem #1, but the coefficients change due to the material change.

K_5 = 0.610, K_6 = 0.278, K_7 = 0.111, K_8 = 0.348

Solve for theoretical window thickness:

$$S_{des} = 2000 = 0.610(15)\left(\frac{10}{t}\right)^2$$

$t = 0.676”$ use 1 1/16" (0.688”)

Check for deflection limit:

$$w = \frac{0.111(15)\ (10)^4}{3.25x10^5\ (.688)^3} = 0.0157” \langle \frac{t}{2} = 0.344”$$

$$S_a = 0.610(15)\left(\frac{10}{.688}\right)^2 = 1933 \text{ PSI}$$

$$S_b = 0.278(15)\left(\frac{10}{881}\right)^2 = 881 \text{ PSI}$$

$$\theta_{max} = \frac{0.348(15)(10)^3}{3.25x10^5\ (.688)^3} = 0.0016\ \text{RAD}\ (0.092°)$$

Problem #3

All equation and coefficients are the same as those of Problem #2.

Solve for theoretical window thickness:

$$S_{des} = 2000 = 0.610(3)\left(\frac{10}{t}\right)^2$$

$$t = 0.302 \text{ use } 5/15" = (0.3\ 13")$$

Check for deflection limit:

$$w = \frac{0.111(3)(10)^4}{3.25x10^5\ (.313)^3} = 0.334 \rangle \frac{t}{2} = 0.152"$$

Appendix "A" does not apply, use Appendix "B"

Problem #4

All equations and coefficients are the same as those of Problem #3.

Solve for theoretical window thickness:

$$S_{des} = 2000 = 0.610(5)\left(\frac{10}{t}\right)^2$$

$$t = 0.390"$$

Check for deflection limit:

$$w = \frac{0.111\ (5)\ (10)^4}{3.25x10^5\ (.390)^3} = 0.287 \rangle \frac{t}{2} = 0.152.$$

Appendix "A" does not apply, use Appendix "B"

E. Elliptical Windows

$S_{des} = S_a = K_1 P (a/t)^2$ @ Center

$S_b = K_2 P (a/t)'$ @ Center

$w_{mu} = K_3 P a^4/Et^3$ @ Center

$\theta_{max} = K_4 P a^3/Et^3$ @ Edge along "a" axis

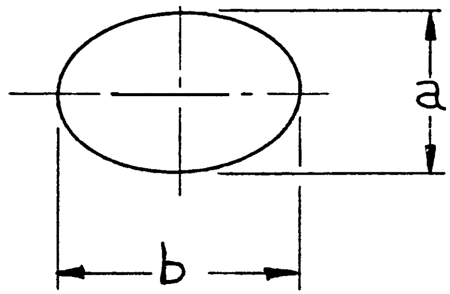


TABLE A-1

ELLIPTICAL PLATE COEFFICIENTS

	K_1 Stress - "a" direction			K_2 Stress - "b" direction			K_3 Deflection			K_4 Edge Slope		
b/a	$\gamma = 0.3$	$\gamma = 0.22$	$\gamma = 0.16$	$\gamma = 0.3$	$\gamma = 0.22$	$\gamma = 0.16$	$\gamma = 0.3$	$\gamma = 0.22$	$\gamma = 0.16$	$\gamma = 0.3$	$\gamma = 0.22$	$\gamma = 0.16$
1.0	0.309	0.302	0.296	0.309	0.302	0.296	0.044	0.048	0.051	0.131	0.146	0.158
1.1	0.353	0.346	0.340	0.323	0.308	0.296	0.052	0.057	0.061	0.158	0.174	0.187
1.2	0.392	0.385	0.380	0.329	0.308	0.293	0.060	0.066	0.070	0.186	0.202	0.216
1.3	0.423	0.417	0.411	0.335	0.305	0.287	0.067	0.073	0.078	0.212	0.229	0.242
1.4	0.455	0.449	0.443	0.335	0.301	0.279	0.073	0.080	0.086	0.235	0.253	0.267
1.5	0.482	0.476	0.471	0.333	0.294	0.270	0.079	0.086	0.092	0.258	0.277	0.292
2.0	0.569	0.564	0.559	0.315	0.258	0.222	0.099	0.108	0.116	0.342	0.363	0.379
3.0	0.650	0.647	0.644	0.282	0.204	0.159	0.118	0.129	0.138	0.416	0.439	0.454
4.0	0.698	0.696	0.695	0.276	0.180	0.130	0.126	0.139	0.148	0.438	0.460	0.473
5.0	0.728	0.728	0.728	0.255	0.167	0.120	0.131	0.144	0.152	0.445	0.465	0.476
∞	0.750	0.750	0.750	0.225	0.165	0.120	0.143	0.149	0.152	0.447	0.467	0.478

C. Rectangular Windows

$S_{der} = S_a = K_5 P (a/t)^2$ @ Center $S_b = K_6 P (a/t)^2$ @ Center

$w_{mu} = K_7 P a^4/Et^3$ @ Center

$r_{mu} = K_8 P a^3/Et^3$ @ Edge along "a" axis

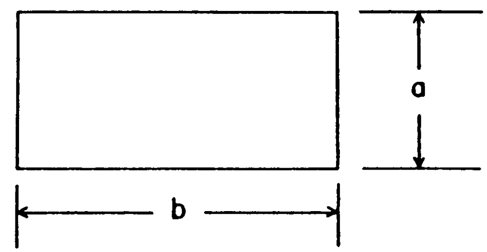


TABLE A-2

RECTANGULAR PLATE COEFFICIENTS

	K_5 stress - "a" direction			K_6 Stress - "b" direction			K_7 Deflection			K_8 Edge Slope		
b/a	y = 0.3	y = 0.22	y = 0.16	y = 0.3	y = 0.22	y = 0.16	y = 0.3	y = 0.22	y = 0.16	y = 0.3	y = 0.22	y = 0.16
1.0	0.286	0.268	0.255	0.286	0.268	0.255	0.044	0.046	0.048	0.139	0.147	0.149
1.1	0.332	0.315	0.302	0.296	0.275	0.256	0.053	0.055	0.057	0.166	0.174	0.178
1.2	0.376	0.359	0.347	0.301	0.276	0.254	0.062	0.064	0.066	0.194	0.202	0.207
1.3	0.416	0.400	0.389	0.302	0.274	0.249	0.070	0.073	0.075	0.219	0.229	0.234
1.4	0.453	0.439	0.428	0.301	0.270	0.242	0.077	0.081	0.082	0.242	0.253	0.259
1.5	0.487	0.473	0.463	0.299	0.264	0.234	0.084	0.088	0.090	0.265	0.277	0.284
2.0	0.610	0.602	0.595	0.278	0.232	0.191	0.111	0.116	0.118	0.348	0.363	0.372
3.0	0.713	0.710	0.709	0.244	0.187	0.138	0.134	0.140	0.143	0.420	0.439	0.449
4.0	0.741	0.740	0.739	0.230	0.171	0.120	0.140	0.146	0.150	0.440	0.460	0.471
5.0	0.748	0.748	0.748	0.226	0.167	0.120	0.142	0.148	0.152	0.445	0.465	0.476
∞	0.750	0.750	0.750	0.225	0.165	0.120	0.142	0.149	0.152	0.447	0.467	0.478

APPENDIX B

I. Symbol Definition

Symbol		Description	Unit
a		Shortest Span	Inch
b		Longest span	Inch
t		Thickness	Inch
p		Uniform Pressure Load	PSI
w		Deflection (Max at center)	Inch
θ		Edge Slope (positive - up to the right)	Radians
S_{des}		Design Stress (Table II)	PSI
E		Elastic Modulus (Table II)	PSI
S_a		Calculated Stress - "a" direction	PSI
S_B		Calculated Stress - "b" direction	PSI
K1	Round Windows	Coefficient for Stress - Center	
K2		Coefficient for Stress - Edge	
K3		Coefficient for Deflection - Center	
K4		Coefficient for Edge Slope	
K5	Rectangular/ Elliptical Windows	Coefficient for Stress - "a" direction - center	
K6		Coefficient for Stress - "b" direction - center	
K7		Coefficient for Deflection - center	
K8		Coefficient for Edge Slope - "a" direction	
K9		Coefficient for Edge Slope - "b" direction	

II. Membrane Theory

A. Limiting Conditions

1. Maximum calculated deflection must be greater than ten times the actual window thickness. (Cannot be glass or brittle material)
2. The pressure load must be uniformly distributed over the entire window surface.
3. All edges will be classed "Held-But-Not-Fixed."
4. The limiting case for elliptical windows is equivalent to rectangular windows (the deflection and stress calculated by this assumption will be slightly greater than the correct values).
5. The lower limiting case for rectangular windows is square, (b/a) = 1.
6. The lower limiting case for elliptical windows is circular.
7. All coefficients and equations are based on material from "Theory of Plates and Shells" - Timoshenko - 2nd edition.
8. Maximum calculated stress must be equal to or less than the design stress tabulated in Table II.

Problem #3

Window Mount Design must conform to Figure #16 or Figure #17.

Using b/a in Table B-l

$$S_{des} = S_a = K_5 \sqrt[3]{E\left(\frac{pa}{t}\right)^2} \qquad K_5 = 0.340$$

$$S_b = K_6 \sqrt[3]{E\left(\frac{pa}{t}\right)^2} \qquad K_6 = 0.085$$

$$w = K_7 \sqrt[3]{\frac{pa^4}{Et}} \qquad K_7 = 0.357$$

$$\theta_a = K_8 \sqrt[3]{\frac{pa}{Et}} \qquad K_8 = 1.428$$

$$\theta_b = K_9 \sqrt[3]{\frac{pa}{Et}} \qquad K_9 = 0.714$$

Solve for theoretical window thickness:

$$S_{des} = 2000 = 0.340 \sqrt[3]{3.25 \times 10^5 \left[\frac{(3)\ (10)}{t}\right]^2}$$

$$t = 0.038''$$

Check for deflection limit: $w \geq 10t$

$$w = 0.357 \sqrt[3]{\frac{(3)(10)^4}{3.25 \times 10^5(.038)}} = 0.480)\ \ 0.380$$

$$S_b = 0.085 \sqrt[3]{3.25 \times 10^5\left[\frac{(3)(10)}{.038}\right]^2} = 499 \text{ PSI}$$

$$\theta_a = 1.428 \sqrt[3]{\frac{3\ (10)}{3.25 \times 10^5(.038)}} = 0.192 \text{ RAD } (10.90°)$$

$$\theta_b = 0.714 \sqrt[3]{\frac{3(10)}{3.25 \times 10^5(.038)}} = 0.096 \text{ RAD } (5.5°)$$

NOTE: The window mount design must have adequate radius at the edges to prevent cutting due to θ_a and θ_B.

Problem #4

All equations and coefficients are the same as those of Problem #3.

Solve for theoretical window thickness:

$$s_{des} = S_a = 2000 = 0.34 \sqrt[3]{3.25 \times 10^5\left[\frac{(5)(10)}{t}\right]}$$

$$t = 0.063$$

Check for deflection limit:

$$w = 0.357 \sqrt[3]{\frac{5\ (10)^4}{3.25 \times 10^5(.069)}} = 0.481\ (\ 0.630$$

Appendix "B" does not apply, use Appendix "C"

1.4.2

B. Circular Windows

Center

$$S_{des} = S_a = K_1 \sqrt[3]{E\left(\frac{pa}{t}\right)^2}$$ $K_1 = 0.266$

Edge

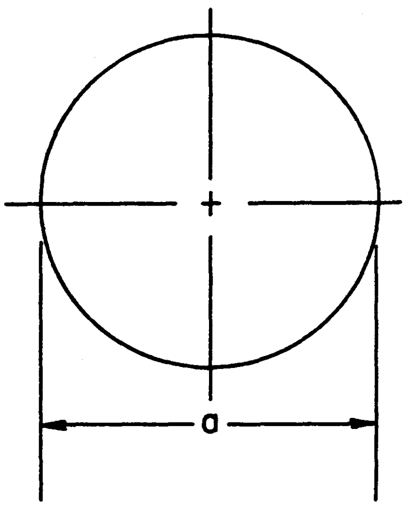
$$S_a = K_2 \sqrt[3]{E\left(\frac{pa}{t}\right)^2}$$ $K_2 = 0.207$

Center (maximum)

$$w = K_3 \sqrt[3]{\frac{pa^4}{Et}}$$ $K_3 = 0.263$

Edge

$$\theta = K_4 \sqrt[3]{\frac{pa}{Et}}$$ $K_4 = 1.210$



C. Rectangular/Elliptical Windows

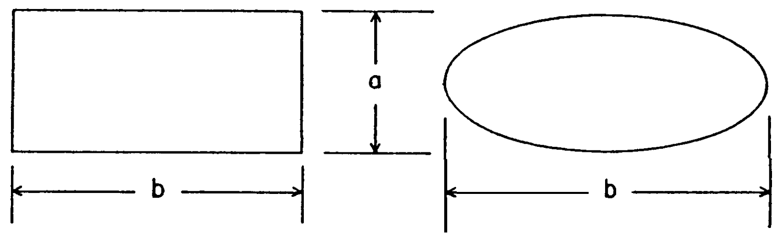
S_{dcs} = sa = $K_5 \sqrt[3]{E\,(pa/t)^2}$ @ Center

$S_b = K_6 \sqrt[3]{E\,(pa/t)^2}$ @ Center

$w = K_7 \sqrt[3]{(pa^4/Et)}$ @ Center

$\theta_a = K_8 \sqrt[3]{(pa/Et)}$ @ Edge

8, $= K_9 \sqrt[3]{(pa/Et)}$ @ Edge



RECTANGULAR/ELLIPTICAL MEMBRANE COEFFICIENTS

b/a	K_5 Stress - "a" direction center	K_6 Stress - "b" direction center	K_7 Deflection	K_8 Edge Slope - 'a' direction	K_9 Edge Slope - "b" direction
1.0	.273	.273	.320	1.280	1.280
1.1	.292	.241	.331	1.324	1.204
1.2	.306	.213	.339	1.356	1.130
1.3	.316	.187	.344	1.376	1.058
1.4	.323	.165	.348	1.392	0.994
1.5	.329	.146	.351	1.404	0.936
1.6	.332	.130	.353	1.412	0.883
1.7	.336	.116	.355	1.420	0.835
1.8	.338	.104	.356	1.424	0.791
1.9	.340	.094	.357	1.428	0.75
2.0	.340	.085	.357	1.428	0.7 14
3.0	.346	.038	.360	1.440	0.480
∞	.346	-	.360	1.440	-

APPENDIX C

I. Symbol Definition

Symbol	Description	Unit
a	Shortest Span	inch
b	Longest Span	inch
t	Thickness	inch
p	Uniform Pressure Load	psi
w	Deflection (Max at Center)	inch
S_{des}	Design Stress (Table II)	psi
E	Elastic Modulus (Table II)	psi
S	Calculated Stress	psi
K_1	Coefficients for Maximum Deflection	
K_2		
K_3	Coefficients for Stress at Center	
K_4		
K_5	Coefficients for Stress at Edge	
K_6		

II. Thin Plate Theory

A. Limiting Conditions

1. Maximum calculated deflection must be equal to or less than ten times the actual window thickness for all windows classified "held-but-not-fixed."
2. Maximum calculated deflection must be equal to or less than two times the actual window thickness for all windows classified "held and fixed."
3. The limiting case for elliptical windows is equivalent to rectangular windows. (The deflection and stress calculated by this assumption will be slightly greater than the correct values.)
4. The pressure load must be uniformly distributed over the entire window surface.
5. The lower limiting case for rectangular windows is square, (b/a) = 1.
6. The lower limiting case for elliptical windows is circular.
7. All coefficients and equations are based on material from "Theory of Plates and Shells" - Timoshenko - 2nd edition, and "Formulas for Stress and Strain" - Roark - 5th edition.
8. Maximum calculated stress must be equal to or less than the design stress tabulated in Table II.

Problem #4

Assume window edges are "held-but-not-fixed."

Using b/a in Table C-l

1. $$\frac{pa^4}{Et^4} = K_1\left(\frac{w}{t}\right) + K\left(\frac{w}{t}\right)^3$$ $K_1 = 9.0$, $K_2 = 22.0$

2. $$S_{des} = E\left(\frac{t}{a}\right)^2 \left[K_3 \left(\frac{w}{t}\right) + K_4 \left(\frac{w}{t}\right)^2\right]$$ $K_3=5.5$, $K_4=2.7$

Assume a value of window thickness using the value calculated by Appendix "A" (0.390) a maximum, and the value calculated by Appendix "B" (0.063) as a minimum. Solve equation 1 for the ratio $\frac{w}{t}$ by using the algorithm of paragraph D with a programmable calculator or any other convenient means. The $\frac{w}{t}$ is used to calculate the stress by means of equation 2.

Assume t = 3/16" (0.188")

$$\frac{5(10)^4}{3.25 \times 10^6(.188)^4} = 9\left(\frac{w}{t}\right) + 22\left(\frac{w}{t}\right)^3$$

Solving: $\frac{w}{t} = 1.699$ and w = 0.319"

$$S = 3.25 \times 10^5\left(\frac{.188}{10}\right)^2\left[5.5\ (1.699) + 2.7\ (1.699)^2\right]$$

S = 1968 PSI (S_{DES} = 2000 PSI

3/16" thick window is adequate

Problem #4 (Alternate)

Assume the window edges are "Held and Fixed."

Using b/a in Table C-l

Center $- pa^4 = K_1\left(\frac{w}{t}\right) + K_2\left(\frac{w}{t}\right)^3$ $K_1 = 36.1$, $K_2 = 22.0$

Center $- S = \left[K_3\left(\frac{w}{t}\right) + K_4\left(\frac{w}{t}\right)^2\right]E\left(\frac{t}{a}\right)^2$ $K_3 = 8.9$, $K_4 = 2.7$

Edge $- S_{des} = \left[K_5\left(\frac{w}{t}\right) + K_6\left(\frac{w}{t}\right)^2\right]E\frac{t}{a}^2$ $K_5 = 18.0$, $K_6 = 2.7$

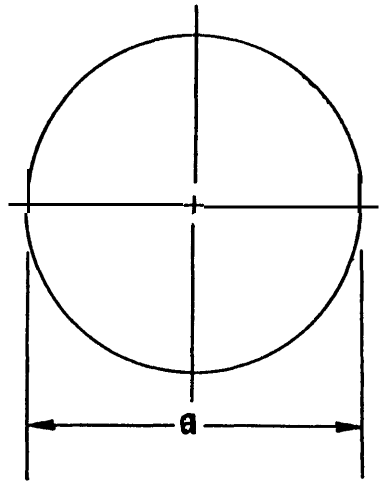
Trial and error produces:

t = 0.353", $\frac{w}{t}$ = 0.263, w = 0.093

Notes: 1. The thickness of the window is almost equal to that of Appendix "A."

2. The thickness (3/16") calculated for the "Held-but-not Fixed" window mount placed in a "Held and Fixed" mount would reach yield point stress at the edge. The material would yield locally until the stress at the center would limit the deflection to (0.319)". The low values of Elastic Modulus and Yield Point Stress of most plastics make a "Held and Fixed" design impossible to obtain.

B. Circular Windows



1. "Held-But-Not-Fixed"

a. Deflection - Maximum at Center

$$\frac{pa^4}{Et^4} = K_1\left(\frac{w}{t}\right) + K_2\left(\frac{w}{t}\right)^3$$

b. Total Tensile Stress - Maximum at Center

$$S_{des} = S = E\left(\frac{t}{a}\right)^2\left[K_3\left(\frac{w}{t}\right) + E_4\left(\frac{w}{t}\right)^2\right]$$

1. "Held and Fixed"

a. Deflection - Maximum at Center

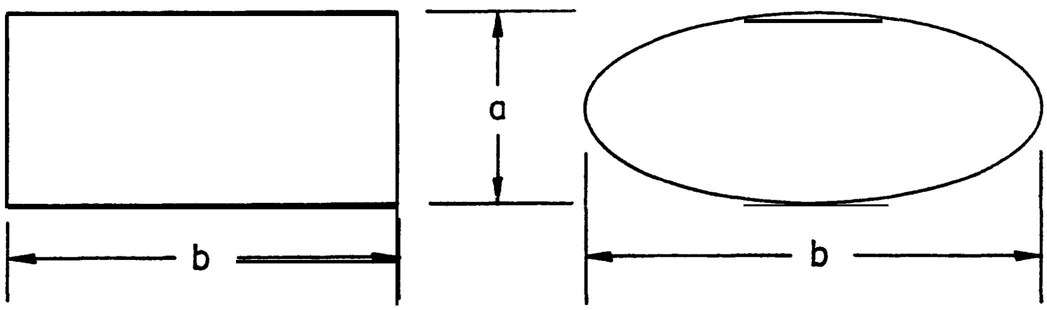
$$\frac{pa^4}{Et^4} = K_1\left(\frac{w}{t}\right) + K_2\left(\frac{w}{t}\right)^3$$

b. Total Tensile Stress

$$S = E\left(\frac{t}{a}\right)^2\left[K_3\left(\frac{w}{t}\right) + K_4\left(\frac{w}{t}\right)^2\right]$$

$$S_{des} = S = E\left(\frac{t}{a}\right)^2\left[K_5\left(\frac{w}{t}\right) + K_6\left(\frac{w}{t}\right)^2\right] - \text{Max at Edge}$$

C. Rectangular/Elliptical Windows



1. "Held-But-Not-Fixed"

a. Deflection - Maximum at Center

$$\frac{pa^4}{Et^4} = K_1\left(\frac{w}{t}\right) + K_2\left(\frac{w}{t}\right)^3$$

b. Total Tensile Stress - Maximum at Center

$$S_{des} = S = E\left(\frac{t}{a}\right)^2\left[K_3\left(\frac{w}{t}\right) + E_4\left(\frac{w}{t}\right)^2\right]$$

2. "Held and Fixed"

a. Deflection - Maximum at Center

$$\frac{pa^4}{Et^4} = K_1\left(\frac{w}{t}\right) + K_2\left(\frac{w}{t}\right)^3$$

b. Total Tensile Stress - at Center

$$S = E\left(\frac{t}{a}\right)^2\left[K_3\left(\frac{w}{t}\right) + K_4\left(\frac{w}{t}\right)^2\right]$$

Maximum stress occurs at the midpoint of the long (b) edge.

$$S_{DES} = S = E\left(\frac{t}{a}\right)^2\left[K_5\left(\frac{w}{t}\right) + K_6\left(\frac{w}{t}\right)^2\right]$$

D. ***Calculation Procedure***

1. In all cases the cubic equation must be solved for (w/t) as the first step. The value of (w/t) can best be found by estimating (w/t) and then refining the estimate using "Newton's Method" and iteration:

$$\left(\frac{w}{t}\right)_{n+1} = \left(\frac{w}{t}\right)_n - \frac{K_2\left(\frac{w}{t}\right)_n^3 + K_1\left(\frac{w}{t}\right)_n - \frac{pa^4}{Et^4}}{3K_2\left(\frac{w}{t}\right)_n^2 + K_1}$$

where:

$$n = 1,2,3,\ \text{etc.}$$

Table C-l

THIN PLATE COEFFICIENTS

Shape	Edge Cond.	b/a	K,	K,	K_3	K_4	K_5	K_6
Circular	Held-But-Not-Fixed	1	23	55	7.1	3.8	--	--
Circular	Held and Fixed	1	93.5	55	11.4	3.8	17.5	3.0
Rect.	Held-But-Not-Fixed	1.0	22.5	30.5	6.5	2.7	--	--
		1.1	18.9	27.6	6.3	2.7	--	--
		1.2	16.2	25.7	6.1	2.7	--	--
		1.3	14.3	24.6	5.9	2.7	--	--
		1.4	13.0	23.7	5.9	2.7	--	--
		1.5	11.9	23.1	5.8	2.7	--	--
		1.6	11.0	22.7	5.7	2.7	--	--
		1.8	9.8	22.2	5.6	2.7	--	--
		2.0	9.0	22.0	5.5	2.7	--	--
		3.0	7.5	21.4	5.3	2.7	--	--
Rect.	Held-But-Not-Fixed	∞	7.0	21.4	5.3	2.7	--	--
Rect.	Held and Fixed	1.0	72.5	30.5	10.0	2.7	22.3	2.7
		1.1	60.9	27.6	9.7	2.7	21.3	2.7
		1.2	53.2	25.7	9.5	2.7	20.4	2.7
		1.3	47.9	24.6	9.4	2.7	19.7	2.7
		1.4	44.3	23.7	9.3	2.7	19.3	2.7
		1.5	41.5	23.1	9.2	2.7	18.9	2.7
		1.6	39.8	22.7	9.1	2.7	18.7	2.7
		1.8	37.5	22.2	9.0	2.7	18.3	2.7
		2.0	36.1	22.0	8.9	2.7	18.0	2.7
Rect.	Held and Fixed	∞	35.2	21.4	8.8	2.7	17.6	2.7

APPENDIX D

-- Plastic materials unlike metals are not elastic; they are "visco-elastic." As a result, stress-strain curves determined by standard ASTM tests are difficult to interpret correctly because ultimate properties (values at failure) do not give a true indication of the performance of plastic materials.

A plastic material may follow any one of the three stress-strain curves (Fig. 1, page 34) depending on temperature conditions. This figure shows the proportional limit (the point at which the modulus line determined in tensile tests diverges from the actual curve) which determines the continuous loading possible for a particular plastic material. All parts designed to this proportional limit will be safe; all parts designed to the yield point strength or break point will fail.

Creep

An equation has long been needed by which long-term creep could be predicted,but such an equation is not completely possible because of the many factors which must be considered. At present the most precise method of determining such data is long-term test at various levels of stress and temperature.

Figure 2, page 35 gives comparative creep curves under one set of conditions. Curves for different conditions are available from manufacturers.

Apparent Modulus

Determined in conjunction with creep, apparent modulus represents the actual strain at a given stress level over a designated period of time. Figure 3, page 36 gives apparent modulus vs. time, at room temperature for different materials.

Creep and apparent modulus can be used to determine deflections over a given period. A true creep resistant material would have no change in deflection, and its apparent modulus would be equal to an instantaneous modulus. Figures 2 and 3, pages 35 and 36 indicate that plastics materials differ greatly and that, if creep is important for a particular application the various materials will have to be checked for best results.

Tensile Modulus:

Figure 4, page 37 shows how tensile Modulus (by ASTM procedures) varies from plastic to plastic.

Tensile, compressive, flexural and shear strengths of these materials vary, greatly, with temperature. It must be remembered that strengths shown inproperty figures are instantaneous values at room temperature.

Impact:

Data on impact strengths of various plastics and metals are valid only for direct comparisons; they have little value otherwise because impact resistance of a finished part depends so much on part shape, impact rate, and other considerations that: prototype testing is required.

Allowable Working Stress:

In general, working stress values are not included in available property figures. Figure 5, page 38 compares some of the engineering plastics according to values published by various manufacturers. It demonstrates the changes that occur when temperature is raised. The curves show how the allowable continuous load of a part decreases with rising temperature and that the allowable continuous stresses for plastics are far below the instantaneous strength values shown in property figures 1 through 5. Yet these continuous stress limits are the values to which plastic parts must be designed if long term reliability is to be achieved.

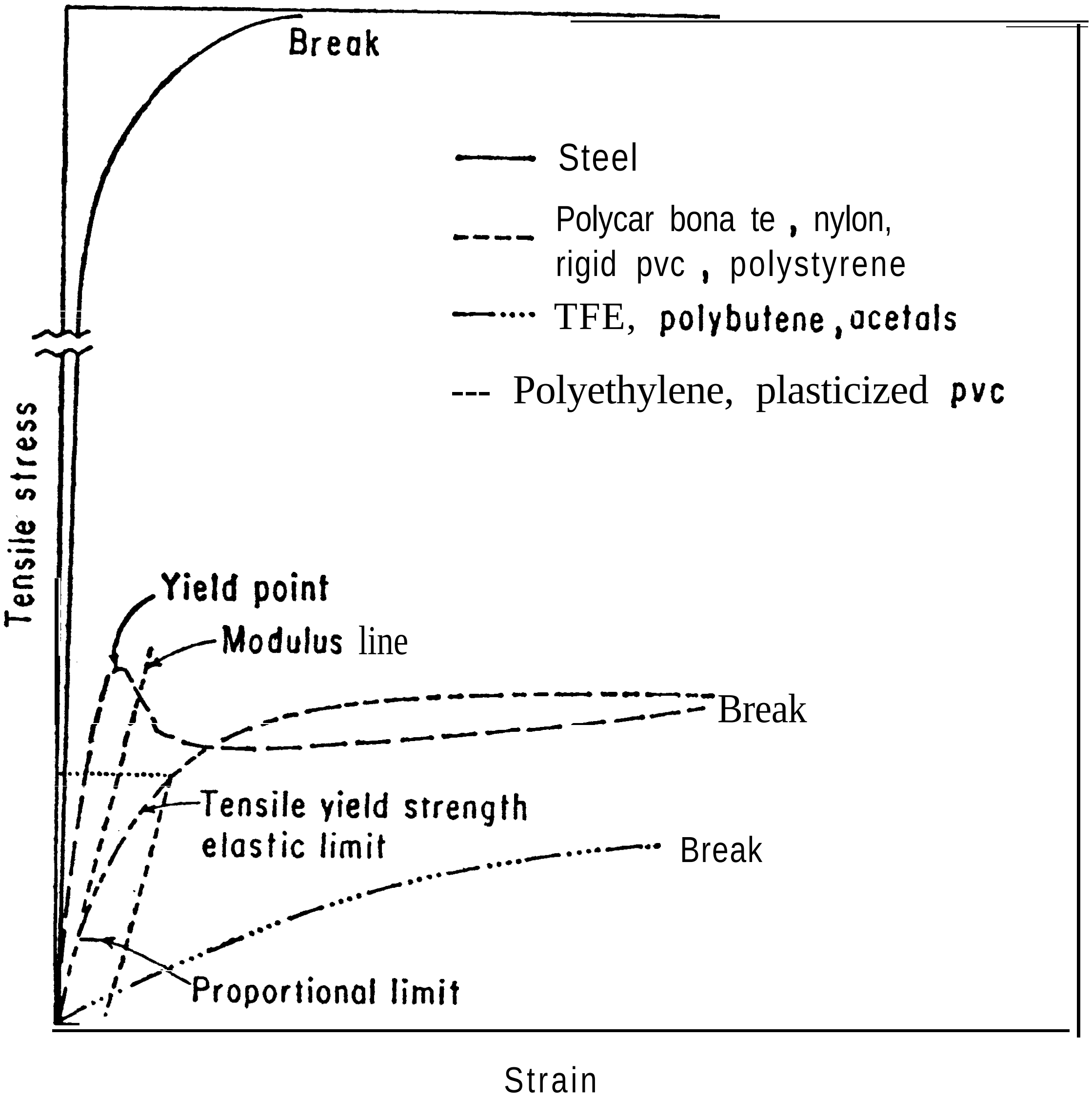


FIG. **1:** Three typical stress-strain curves.

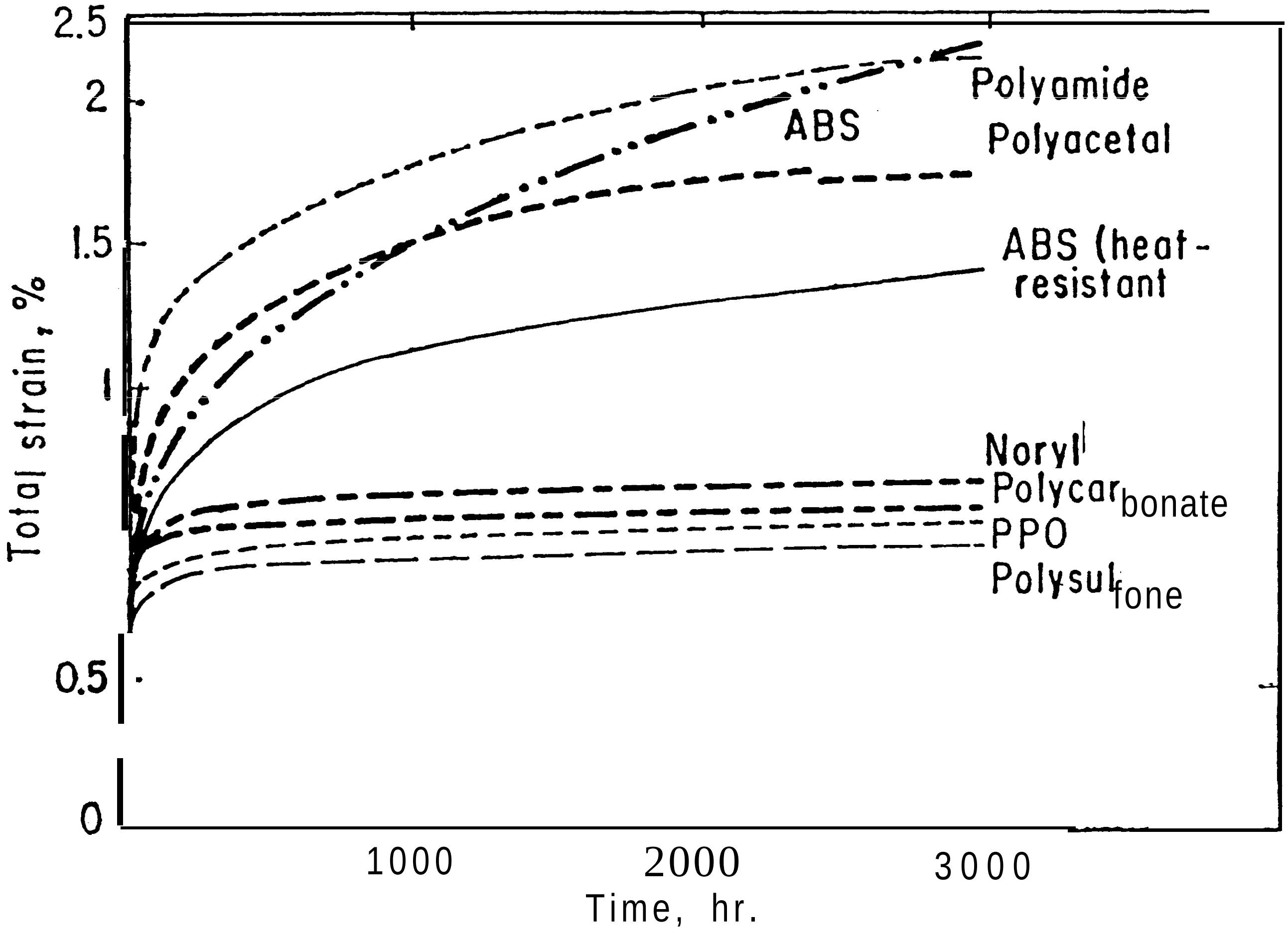


FIG. 2: Comparative creep behavior at 73° F.

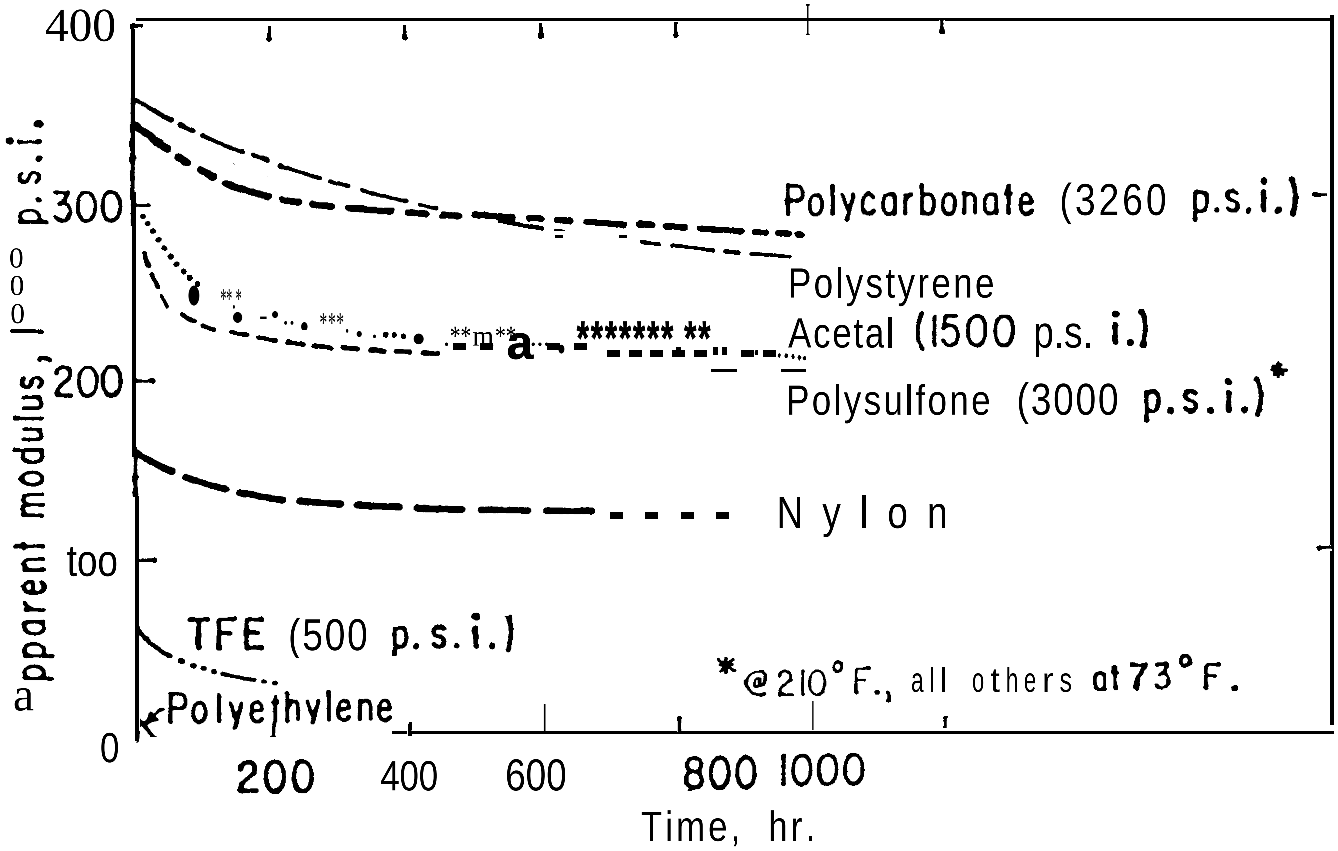


FIG. 3: Variation of apparent modulus with time.

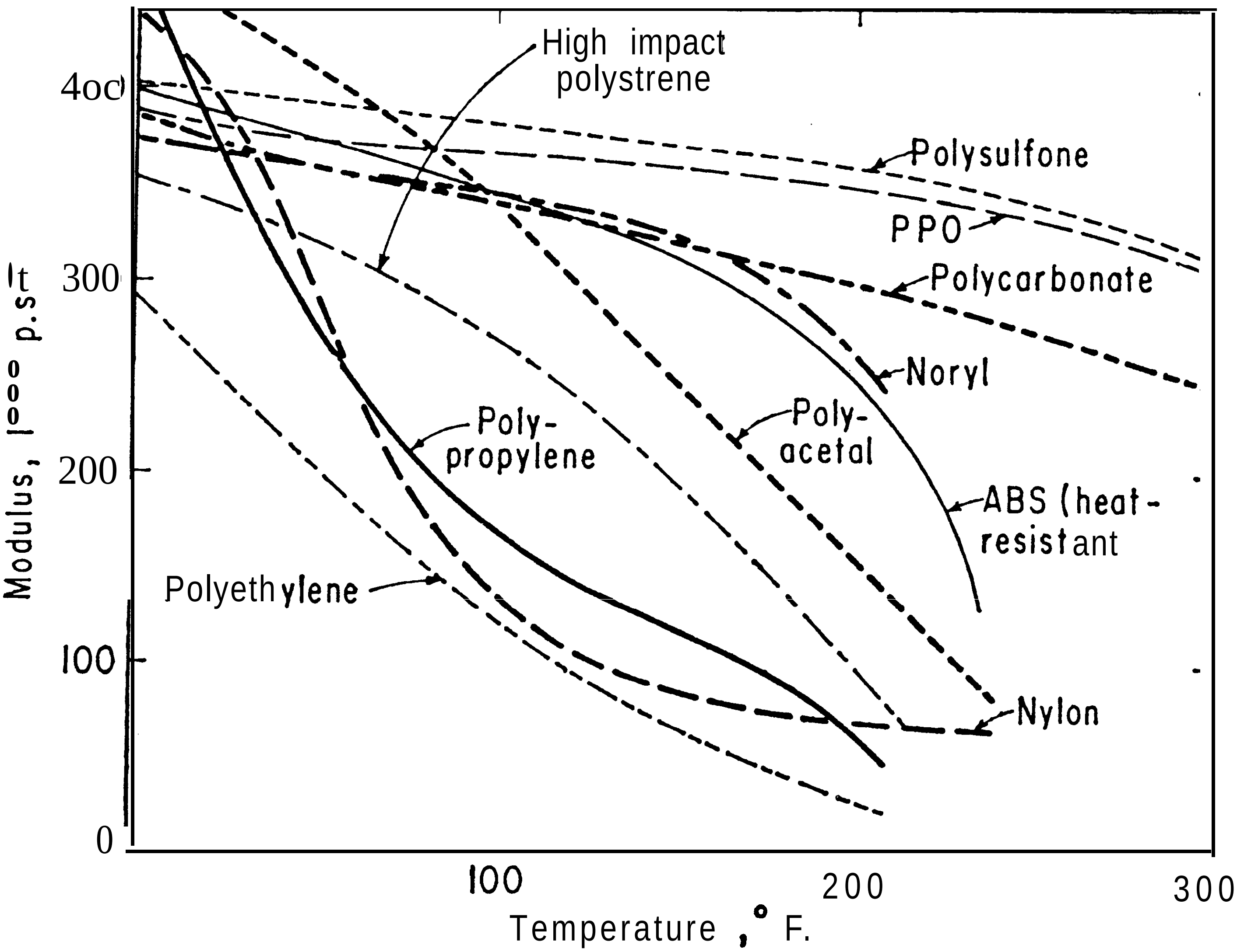


FIG. 4: Tensile modulus vs. temperature.

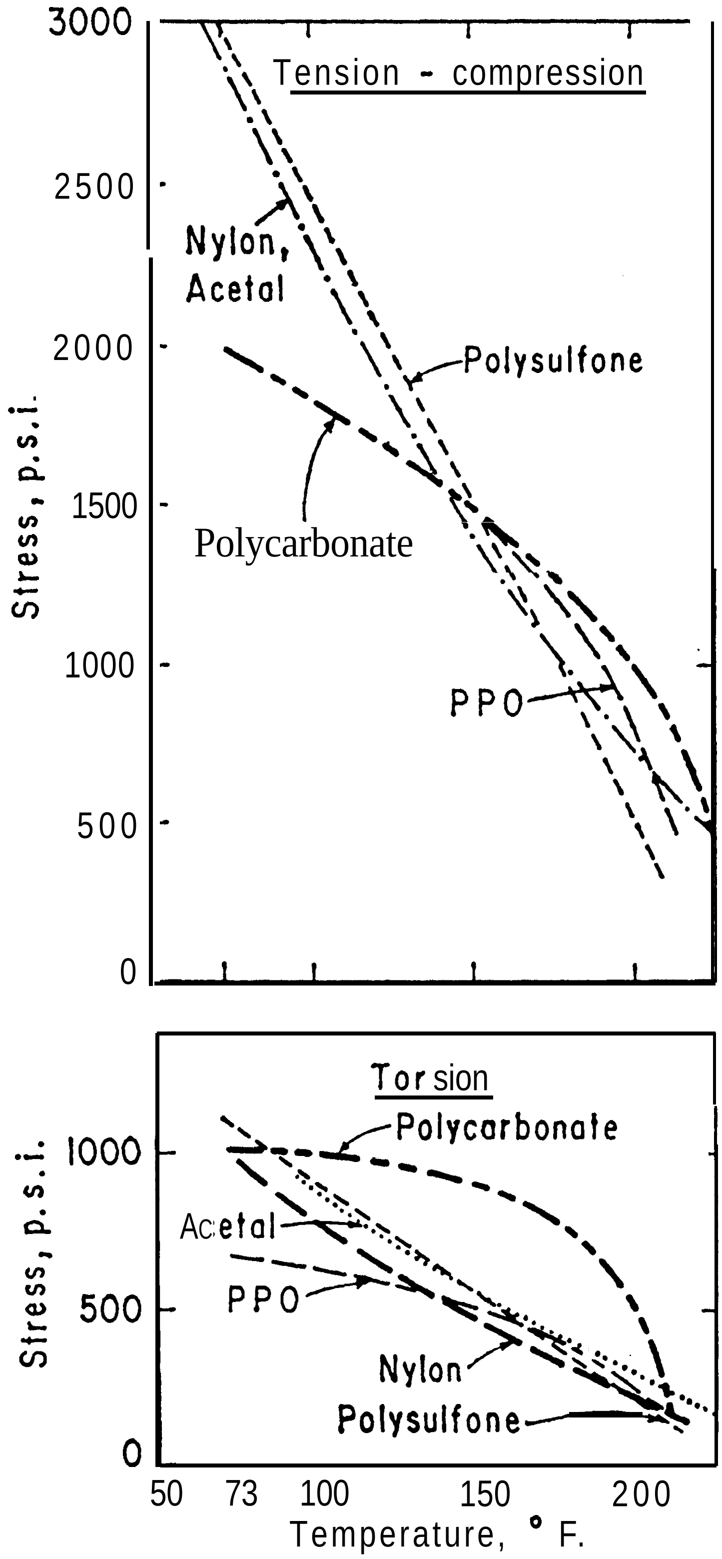


FIG. 5: Continuous allowable stress vs. temperature.

REFERENCES

1 - Data extracted from Corning Code No. 7940 "Fused Silica"

2 - Data extracted from "Design & Engineering Data" for duPont Lucite

3 - Coming Data Sheets

4 - Pittsburgh Plate Glass - Engineering Data

5 - Journal of Applied Physics, Volume 28, No. 5, 610-614, May 1957, Kropschot & Mikesell

6 - General Electric - Product Data "Lexan" Polycarbonate Sheet Series 9400, September 1966

7 - Modern Plastics Encyclopedia

8 - Variations in properties between different manufacturers of "methyl-methacrylate" requires a design stress limited to the lower value as determined by either of the following:

(a) $S_{design} = \dfrac{\text{Modulus of Rupture}}{10}$ (at T°F)

(b) $S_{design} \dfrac{9200}{10} \quad \dfrac{\text{Elastic Modulus at T°F}}{360{,}000}$ (at °F)

9 - Before any elevated temperature operations on thickness greater than 0.093" are attempted for polycarbonate, it is necessary to remove the very small equilibrium percentage of moisture. Sheet or film that has not been properly dried prior to forming will have a tendency to bubble. Normal forming temperature range for polycarbonate is 350°F to 400°F. (Note #7)

#10 - Roark - 3rd Edition, page 219, par. 58

#11 - Glass Engineering Handbook, E. B. Shand, 2nd Edition, 1958, page 264

#12 - Machine Design, March 11, 1965, page 24

#13 - Effect of Radiation on Mechanical Properties, Fig. 6-13, pages 23 through 26 has been extracted from "Selection Guide to Organic Materials for Nuclear Engineering, CERN 72-7, Laboratory I, Intersecting Storage Rings Division, 17 May, 1972"